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Computational study on flow structures of quench zone in a rich-quench-lean trapped-vortex combustor

Bo Jiang [a,b,]* Xiaomin He[a,c], Yi Jin[a], Guoyu Ding[a], Zejun Wu[a]

[a] College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, PR China
[b] Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544, USA
[c] Co-Innovation Center for Advanced Aero-engine, Beijing 100191, PR China

Abstract

The quench zone is one of key issues for a rich-quench-lean(RQL)/trapped-vortex combustor(TVC). The characteristics of flow structures of quench zone were investigated computationally with the correction by the particle image velocimetry(PIV) results. RQL/TVC combines the potential advantages of the low emission staged combustion technology of RQL with TVC. TVC has been a very promising novel combustor concept offering improvements in lean blow-out, altitude relight, and operating range. Besides, compared to conventional combustors, TVC has a potential to decrease nitrogen oxides emissions. By utilizing quench devices with different sizes of holes under the same blockage ratio in mainstream position, this paper describes the characteristics of flow structures of quench zone in a RQL/TVC. The results show that, through the quench devices, the mainstream flow quickly mixes with the flow from the cavity zone under variable mixing levels which are related to the changing of different sizes of holes. The effects of turbulent intensity and unmixedness level were examined and discussed.

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Keywords: RQL/TVC; quench zone; flow structure, turbulent intensity, unmixedness rate

1. Instruction

Combustor is one of the key components in a gas turbine engine and the emission performance of the combustor is essential for aero engines. Low emission performances are achieved by minimizing the formation pollutants, such as nitrogen oxides, carbon monoxide, and unburned hydrocarbon. In order to achieve the goal of ultraclean emission, revolutionary design changes will be required. Recently, Hsu et al[1,2] proposed a new flame stabilization concept known as trapped-vortex combustor (TVC). As a fuel-flexible combustor, the TVC concept can be configured to operate either in rich-quench-lean (RQL) mode or in other staged modes, as a lean premixed combustor with a hybrid approach[3-11].

The quench zone, which connects the rich zone and lean zone, is one of the key parts in RQL combustor. Therefore, a detailed study on the flow structures of the quench zone is of crucial importance for the ultimate success of a RQL/TVC design.

Last 30 years, significant progress in TVC and RQL has been made. The flow field of the classical TVC geometry of Hsu's combustor model has been widely studied[1,2]. Design principles for quench zone of

* Corresponding author. Tel.: +86 151 5050 5250
E-mail address: bojiang815@outlook.com

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RQL combustor had been discussed by Hassa and Migueis[8]. A numerical study on the mixing problem of the RQL quench zone without combustion was undertaken. Anacleto had investigated a typical of RQL gas-turbine combustors based on detailed velocity measurements of the turbulent flow fields in a water model of a can-type combustor[9]. Straub had assessed the approach of utilizing a main air distributor plate to quickly mix the burnt gases from the cavity zone into the mainstream flow in RQL/TVC for stationary gas turbines[10]. Straub et al had carried out detailed 3-D, reacting, computational fluid dynamics(CFD) simulations of a RQL/TVC to evaluate different fuel and air injection configurations, to identify and mitigate the potential high temperature regions, and to improve mixing[11].

As for RQL/TVC models for gas turbine engines, attentions are paid mostly to design and to optimize the combustion characteristics, few detailed flow structure analysis are available, especially for quench zone. This paper proposes a new workable RQL/TVC geometry for aeronautical gas turbine engines and investigates the characteristics of flow structures of quench zone. The performance of different sizes of holes in quench devices under the same blockage ratio and the unmixedness rate had been investigated.

2. Computational domain and numerical method

2.1Computational domain

Fig.1 shows a 2-D schematic of the RQL/TVC and the computational domain. The RQL/TVC consists of a diffuser, cowls, a quench device, cavities, liners and casings. The quench device, as shown in Fig.2, is designed as a plate with different sizes of holes under the same blockage ratio. The monitoring planes for flow fields are shown in Fig.3.

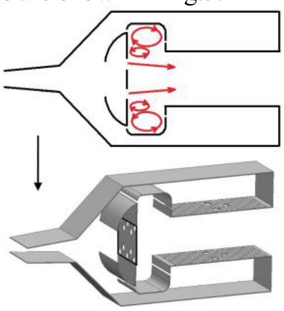


Fig.1 2-D schematic and computational domain

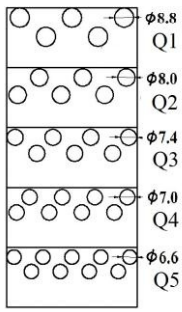


Fig.2 Configurations of quench device

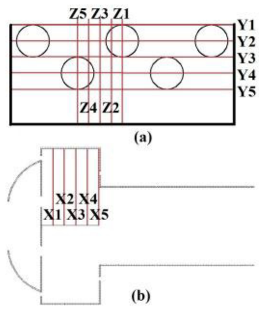
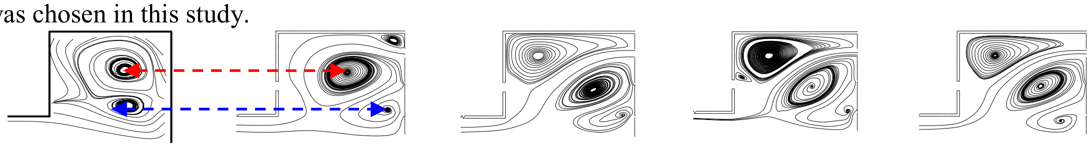


Fig.3 Monitoring planes

2.2 Numerical method

In the present work, the numerical simulations were completed by using the commercial CFD software FLUENT. To simulate the isothermal non-reacting flow field of the combustor, the steady-state continuity and momentum equations are discretized over the computational domain using a finite volume method. Convection and diffusion terms are discretized by the second-order upwind scheme. The well-known SIMPLE algorithm is applied for pressure-velocity coupling. Translational periodical boundary conditions are applied to the two lateral sides of the domain. Mass flow and pressure boundary conditions are employed at the inlet and the outlet respectively. The standard wall functions are utilized to take care of the near-wall region. The turbulence model determination and numerical method validation are accomplished with help of our PIV measurements. Working conditions of the numerical simulations are identical to that of the PIV experiments in Fig. 4[12, 13]. The turbulence model of standard k-ε model was chosen in this study.



(a) PIV measured (b) Standard k-ε (c) SST k-ω (d) RNG k-ε (e) Realizable k-ε

Fig.4 PIV measured and computational streamlines in Z1 (Ma=0.25).

The solution was ensured to be independent from the grid by performing a grid independency study on four different sizes of grids, 2.8M, 3.3M, 3.8M, and 4.4M, respectively. The grid size of 3.8M cells was adopted in the present work.

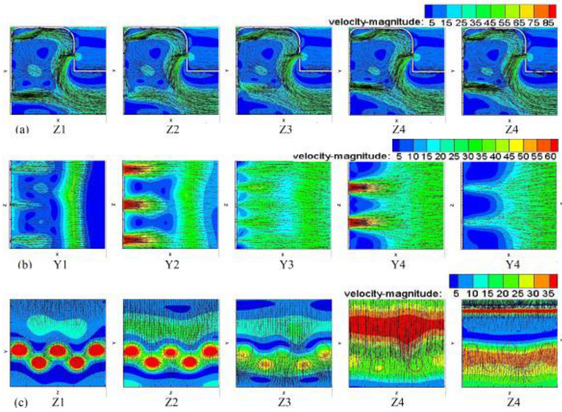
3. Results and discussions

3.1 Flow structures

Fig.5 shows the counters of velocity magnitude and vectors of velocity at Ma=0.25 in monitoring planes of Z1-Z5,Y1-Y5 and X1-X5, these planes' positions were shown in Fig. 3. It is obviously seen from Fig. 5(a) that, the dual-vortex flow structure is clearly existed behind the fore-wall in each monitoring planes of Z1-Z5. The velocity of mainstream rapidly reduces from above 60 m/s in holes to about 20 m/s in penetration distance at less than 4/5 of the cavity width. The penetration distance of mainstreams which are closed to X axis in Z5 is a little longer than those ones further from X axis in Z1. These characteristics also are clearly illustrated in monitoring planes of Y2 and Y4 in Fig. 5(b). The flow fields show a uniform distribution along the downstream direction in Y3-Y5 and X3-X5, after the velocity decreasing to the circumambient value. The vectors of velocity, which located in the left part of Fig. 5(a) and 5(b), and in Fig 5(c), illustrate that the flow from the cavity zone has been transported towards to mainstream direction and mixed with the mainstream. The flow from the cavity zone and mainstream are cross flows, and they interact with each other to make interaction, clearly showing in Y1, Y2 and X1, X2.

3.2 Turbulent intensity and mixing level analysis

Contours of turbulent intensity at Ma=0.25 in the monitoring planes of Z1-Z5 and Y1-Y5 are shown in Fig.6. It is clearly seen that the turbulent intensity in and/or through the holes of quench device is the most strong. The turbulent intensity quickly decreases because of the velocity changing so fast, and the momentum also decreases.



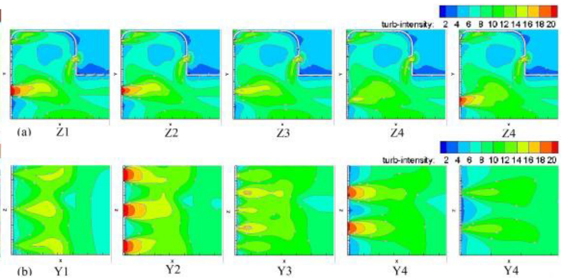


Fig.5 Contours and vectors of velocity magnitude at Ma=0.25 Fig.6 Contours of turbulent intensity at Ma=0.25

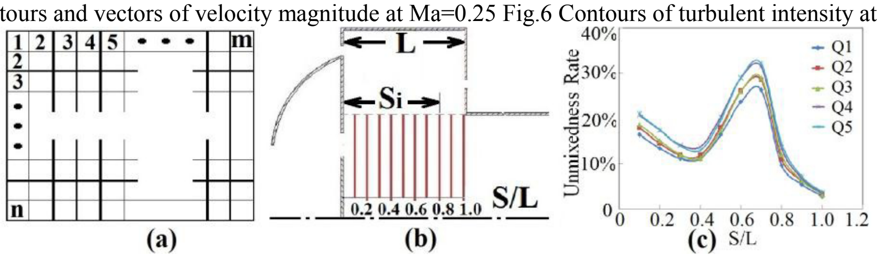


Fig.7 Unmixedness profiles at Ma=0.25 in quench zone

The cells' patterns and the profile of unmixedness rates are shown in Fig. 7.

There is a measure of unmixedness based on the variance of concentration distribution, defined as spatial unmixedness[14-15]: $Us = \dfrac{M_{Var}}{M_{avg}(1-M_{avg})}$, and $M_{Var} = \dfrac{1}{m \times n}\sum_{i=1}^{m}\left(\sum_{j=1}^{n}\left(M(i,j)-M_{avg}\right)^2\right)$

M_{avg} =average concentration at a cell, M_{Var} =fully mixed concentration.

4. Conclusions

In this paper, the characteristics of the flow structures of the quench zone in a RQL/TVC were investigated by computationally with the validation by the PIV results. Quench devices with different sizes of holes under the same blockage ratio have been utilized in the mainstream. In this condition, the flow structure, turbulent intensity and mixing level have been analysed.

The results show that the dual-vortex exists and displays variable sizes and different core positions of the vortexes. The secondary vortex transports the flow from cavity zone into the mainstream. Meanwhile the mainstream penetrates into the lower turbulent intensity flow from the cavity zone, and the penetration distance of mainstream is less than 4/5 of the cavity width. The vectors of velocity illustrate that the flow from the cavity zone has been transported towards to the mainstream direction and mixed with the mainstream. The flow from the cavity zone and mainstream are cross flows, and they interact with each other. The counter of turbulent intensity gives the values changing along with local velocity. At last, a measure of unmixedness based on the variance of concentration distribution has been used to quality the unmixedness rate of monitoring planes along the downstream direction, and Q1 quench device has the lowest unmixedness rate nearby 3%.

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